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RER: a Real time Energy efficient Routing protocol for query-based applications in Wireless Sensor Networks

Ehsan Ahvar · Gyu Myoung Lee · Noel Crespi · Shohreh Ahvar

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Abstract Energy-aware routing protocols can be classified into two categories, energy savers and energy balancers. Energy saver protocols are used to minimize the overall energy consumed by a wireless sensor network (WSN), while energy balancer protocols efficiently distribute the consumption of energy throughout the network. Energy saver protocols are not necessarily good at balancing energy consumption and energy balancer protocols are not always efficient at reducing energy consumption. On the other hand, although delay is another important factor for WSNs energy-aware protocols do not take care of it. This paper proposes a Real time Energy efficient Routing(RER) protocol for query-based applications in WSNs, which offers an efficient trade-off between traditional energy balancing and energy saving objectives while supporting a soft real time packet delivery. This is achieved by means of fuzzy sets and learning automata techniques along with zonal broadcasting to decrease total energy consumption.

Keywords Wireless sensor network · Routing protocol · Real time · Energy efficient

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1 Introduction

A Wireless Sensor Network (WSN) includes some sensor nodes, which are deployed either inside the phenomenon or very close to it [2]. Basically, each sensor node has capability of sensing, packet transmission, data processing, mobility, and location finding. However, some of these capabilities can be optional, such as mobility. Sensor nodes can coordinate with each other to get high-quality information about the physical environment. These nodes have the ability to communicate amongst each other. They sometimes can directly communicate to an external station.

Because sensors are generally battery-powered nodes, the critical aspects to face concern how to improve the power consumption of sensor nodes, so that the network lifetime can be extended to reasonable time [3]. As the battery carried by each mobile sensor node has a limited power supply, computing power is limited, which in turn limits supported services by each node. This restriction is considered as a serious challenge in WSNs, where each node has to act as both an end system and a router node at the same time and, therefore, additional energy is needed to send packets to other nodes.

Many routing algorithms and protocols have been proposed for different types of WSNs (i.e., [4, 5], [8–13], [15–18], [20], [22, 23]) among which we have identified a category known as query-based routing. For this category, a station S sends queries to find specific events among the WSNs. The strategies used for routing these queries and their corresponding replies can be classified into two major groups, energy savers and energy balancers. The former tries to decrease the energy consumption of the network as a whole and thereby increase the operation lifetime which also usually leads to the utilization of the shortest paths. The latter, on the other hand, tries to balance the energy consumption of the nodes to prevent partitioning of the network.

Rumor is an energy saving protocol that provides an efficient mechanism combining push and pull strategies to obtain the desired information from the network [6]. In Rumor, the nodes generating events send notifications that leave a sticky trail along the network. When query agents visit a node where an event notification agent has already passed through, they can find pointers (i.e., the trail) towards the location of the corresponding source. In general terms, when a node receives a query two things can happen: i) the node already has a route toward the target event, so it only needs to forward the query along the route; or ii) the node does not have a route, and therefore, it forwards the query to a random neighbor. The random selection of the neighbor in this case is relatively constrained, since each node keeps a list of recently visited neighbors to avoid repeatedly visiting them.

Clearly, the forwarding strategy in Rumor could end up producing spiral paths, so an intuitive improvement would be to reduce its level of routing indirection. To this end, Cheng-Fu Chou et al. proposed the Straight Line Routing (SLR) protocol [7], which aims at making the routing path grow as straight as possible. More recently, Shokrzadeh et al. made significant efforts to improve Rumor in different aspects with their Directional Rumor (DRumor) [19]. Shokrzadeh et al. later improved their DRumor protocol by means of what they called the Second Layer Routing (SecondLR) [21]. SecondLR uses geographical routing immediately after locating the source of an event, and Shokrzadeh et al. have shown that this approach considerably improves the performance of DRumor. Despite these efforts, current query-based routing protocols are mainly energy savers, and have shown relatively poor performance when it comes to balancing energy consumption.

Much more recently, Ahvar et al. have proposed the Energy-aware Query-based Routing protocol (EQR), an energy saver and balancer routing protocol [1]. EQR uses zonal broadcasting to reduce energy consumption.

This paper presents a routing strategy applicable to various forms of query-based applications and offers a reasonable trade-off between the energy and delay objectives. More precisely, we propose a Real time Energy efficient Routing protocol for query-based applications in WSNs called the RER, supported by a learning automata, a fuzzy sets and uses zonal broadcasting to decrease the total energy consumed. Our initial results demonstrate the potential and the effectiveness of RER in energy awareness and even in delay, making it a promising candidate for a number of WSN applications.

The rest of the paper is organized as follows. In Section 2, we introduce our design goals. Section 3 presents the main contribution of this paper which is basically the RER routing strategy. The assessment of RER is covered in Section 4, and Section 5 concludes the paper.

2 Design Goals

More specifically, RER satisfies the following design objectives:

- *(1)Energy-distance optimization:* Energy-awareness means both energy saver and energy balancer concepts. Energy saver protocols try to decrease the energy consumption of a network to increase network lifespan. They usually try to find the minimum path length to reduce energy consumption. Energy balancer protocols try to balance the energy consumption of nodes to prevent network partitioning. Finding the best route only based on energy balancing concept may lead to longer paths with greater delay, and finding the best route based only on energy saving concept and optimal distance may lead to network partitioning. The RER is an energy saver and an energy balancer at the same time. It achieves a tradeoff between distance and energy by using learning automata and fuzzy sets techniques.
- *(2)Accuracy:* Finding the best node as a next hop in aspects of energy saving and balancing is a big challenge for routing protocols. Most energy-aware routing protocols find the next hop based on only one measurement factor, such as energy level. The RER, however, considers hop count and distance as well as energy level, simultaneously, utilizing more than one decision-making technique to achieve more exact results.
- *(3)Localized behavior and scalability:* The ability to maintain performance characteristics irrespective of the size of the network is referred to as scalability. Pure localized algorithms are those in which any action invoked by a node should not affect the system as a whole. In these protocols, a node usually uses flooding to discover new paths. In WSNs, where thousands of nodes communicate with each other, broadcast storms may result in significant power consumption and even in a network meltdown. To avoid that situation, most of the distributed operations in RER are localized to achieve high scalability.
- *(4)Soft real time:* Although the main goal of the RER is saving and balancing energy, in time-critical situation this protocol can be changed from a pure energy-aware (normal mode) to a delay-aware (critical mode) routing protocol.
- *(5)Minimal state architecture:* The physical limitations of WSNs, such as large scale, high failure rate, and constrained memory capacity, demand a minimal state approach. The RER only maintains the immediate neighbor's information and so it does not need a large routing table. Thus, its memory requirements are minimal.
- *(6)Link failure detection:* The RER has the ability to find a broken link. Unlike most protocols it does not use the Acknowledge packet to check link stability. The RER verifies links by means of the overhearing technique.

– *(7)Minimal control packet:* In many routing protocols the nodes' energy levels are forwarded to neighbors by Acknowledge packets. The proposed routing protocol uses the overhearing technique for updating energy levels. In most routing protocols, nodes with very low energy levels send a packet to warn their neighbors. The RER instead has a threshold, and when each neighbor forwards a packet, all the neighbors receive it and compare the attached energy level of the sender node to the threshold level. If the sender energy is under the threshold, the sender is considered to be a dead node and will not be selected again as a next hop. Therefore, the proposed protocol does not need an extra packet to announce a dead node. The threshold level is the energy required to send a packet.
– *(8)Mobility:* Although WSNs usually do not need to consider a high degree of mobility but the proposed protocol supports node mobility. Source node can send its query from any place. Our query zone is established on demand and dynamically. Also we consider an expected zone specialized for supporting mobility of destination node.

3 Real time Energy efficient Routing (RER)

This section is divided into three main parts. The first part includes some useful definitions and terms that used in our RER protocol. Second part introduces the RER components and the third part gives a brief, general overview of the RER protocol mechanism.

3.1 Definitions

– *Def.1:*Station. a station or sink node is a node that creates a query packet. In fact, the station is original source of a query packet.
– *Def.2:* Sender node. each node that sends query or data packet is called a sender node. In fact, a sender node is a previous hop of a packet.
– *Def.3:* Destination node. a target node that we try to find it by sending query packet is called destination.
– *Def.4:* Query packet. a query packet is a request packet for receiving information on a particular event.
– *Def.5:* Data packet. when a destination node or an event witnessed node receives a query packet, it creates a data packet and sends back the packet to the station. A data packet includes information that an event witnessed node or a destination node wants to transfer to the station.
– *Def.6:* Neighbor Table. Neighbor Table is a data structure that is created inside each node to store information about its one-hop neighbors.

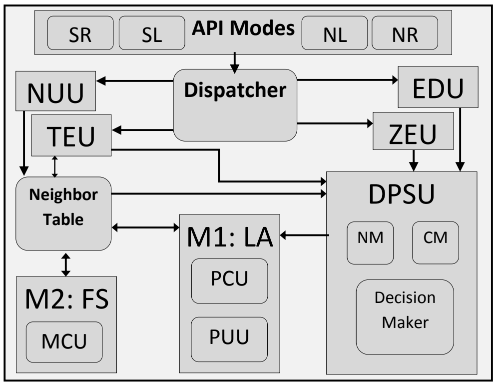


Fig. 1 RER protocol

3.2 RER Components

Our proposed RER protocol basically includes following components:

– *(1)an Application Programming Interface (API),*
– *(2)a Dispatcher module,*
– *(3)a Neighbor Update Unit (NUU),*
– *(4)a Time Estimation Unit (TEU),*
– *(5)a Zone Estimation Unit (ZEU),*
– *(6)a Data Path Selection Unit (DPSU),*
– *(7)a Membership Computation Unit (MCU),*
– *(8)a Probability Computation Unit (PCU),*
– *(9)an Error Detection Unit (EDU) and*
– *(10)a Probability Update Unit (PUU),(see Fig.1).*

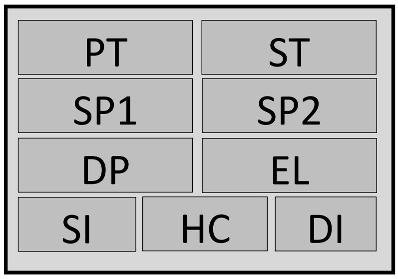
For more clarification, we considered two modules: M1:LA module and M2:FS module. The M1:LA module covers all components of learning automata and the M2:FS is a module related to fuzzy set technique.

In brief, the RER protocol provides four application-level API modes called Non-specific Location (NL), Specific Location (SL), Non-specific Region (NR), and Specific Region (SR) for different type of applications. The ZEU is responsible for estimating the query zone. The Dispatcher is a module responsible for receiving piggybacked information and then transmitting it to the appropriate modules. The NUU gets information from Dispatcher and inserts it into the Neighbor Table. As its name indicates, the EDU is designed to detect errors. The DPSU is the core routing module and hence is responsible for choosing the next hop during the packet forwarding process. The DPSU supports two modes: normal and critical. In normal mode, its Decision Maker (DM) selects an optimum neighbor as the next hop, based on both the membership (from M2 field) degree and the probability (from M1 field) of each neighbor, available in the Neighbor Table (Neighbor Table's fields will be described in Section 3.2.3). The membership degree associated to each neighbor is computed by the MCU (in the M2:FS module) and the probability of each neighbor is computed by the

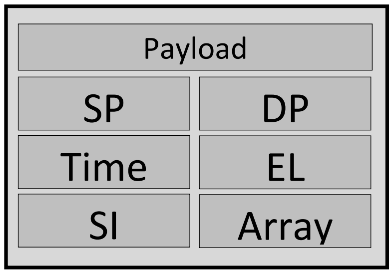
PCU and then updated by the PUU (in the M1:LA module). In critical mode, the TEU alerts the DPSU that there is no enough time to deliver the data packet. Then DPSU triggers the immediate selection of the nearest neighbor to the station as the next hop. The constellation of modules is thus mainly designed to assist the DPSU. We describe each unit in detail in the following sub-sections.

3.2.1 Application API and Packet Format

– *API modes:* As we mentioned the RER protocol supports four application-level API modes: NL, SL, NR and SR. In this architecture, the SR and NR modes are used for event monitoring. The SR is used for applications that monitor events in a specific region of the network, while the NR is used when there is no prior knowledge about where such events occur. In the NR mode, the query packets must be broadcast throughout the entire network to locate potential events.
  The two remaining modes, SL and NL, are designed for querying a given node and getting information directly from it: SL when there is prior knowledge about the expected location of the node, and NL when its location is unknown.
– *Query Packet:* The query packet contains the following fields: Packet Type (PT), Start Time (ST), Sender Id (SI), Destination Id (DI), Sender Position (SP1), Station Position (SP2), Hop Count (HC), Destination Position (DP) and Energy Level(EL)(see Fig.2(a)).
  The PT field indicates the type of communication or mode (SL, SR, NL or NR), ST carries start time of query broadcasting, SI saves the Id of the query-sender node, the destination Id is carried by the DI field in the SL or NL mode's destination. SP1 and SP2 forward the positions of the sender and the station, respectively, and, if available, DP forwards the position of the destination or the center of requested zone. EL indicates the energy level of the sender node and finally HC holds the number of hops from a query sender node to the station.
– *Data Packet:* There is a single data packet format for the RER protocol, which contains the following major fields (see Fig.2(b)).
  Station Id (SI) which is the destination of the data packet or the Id of the station, Payload, an array with a size of 5 that saves the 5 last previous hops to help the PCU to compute probabilities and also to prevent loops, Energy Level (EL) for forwarding the energy level of the data sender node, and Sender Position (SP) which gives the location of the data sender node as well as the Time and Destination Position (DP) fields that indicate the location of the destination node at a certain time so that the query zone in the station can be estimated for a future query. Therefore, the station can update and estimate the position of a destination node more exactly after receiving each data packet from it.



(a) Query packet.



(b) Data packet.

Fig. 2 RER protocol packet formats.

3.2.2 Dispatcher

In the query broadcasting phase, the Dispatcher module will receive information and transmit it to the NUU so it can be inserted into the Neighbor Table. In the response phase, useful information is attached (piggybacked) to the data packet. The Dispatcher will receive piggybacked information from data packet and send each part of that information to the appropriate module.

3.2.3 Neighbor Update Unit (NUU)

The neighbors' information will be recorded in a Neighbor Table. The components of the Neighbor Table for each neighbor are as follows:

– *Neighbor ID (NID):* Holds the Id of a neighbor;
– *Energy Level (EL):* Holds the energy level of the sender's neighbor;
– *Hop Count (HC):* Holds the number of hops from a neighbor to the station;
– *Sender Position (SP1):* Gives the position of the sender (neighbor) node;

- *Station Position(SP2):* Indicates the position of the station;
- *Module1(M1):* Holds the probability associated with a neighbor as computed by the PCU and updated by the PUU; and
- *Module2(M2):* Contains the membership degree associated with a neighbor as computed by the fuzzy set technique

The Neighbor Table also has three global fields:

- *Start Time (ST):* Contains the time that a query packet is sent by the station. The NUU receives the start time from a query packet and inserts it in the ST field.
- *Time to Reach (TTR):* Indicates the estimated time it takes to reach the station from this node; be computed by the TEU.
- *TimeS or time stamp:* Holds the actual receiving time of the data packet. The EDU uses this field for error detection.

As mentioned earlier, there are two types of packets: query and data. The fields of each type of packet have been described in previous sections. After receiving a query packet, the Dispatcher sends the sender Id, energy level, hop count, sender position, and the station position information (also the ST, which will be described subsequently) to the NUU, and then NUU will insert (or update) this data into the Neighbor Table.

The TEU computes the time it takes to go from this node to the station (the TTR) and inserts it into the TTR field. The method used by the TEU to compute the TTR is described in Section 3.2.4. The TimeS or the time stamp field refers to the data packet receiving time. The EDU uses this field for error detection.

After receiving a data packet, the Dispatcher transmits the piggybacked energy level of the sender node to the NUU. The NUU then updates the sender node's energy level in the Neighbor Table.

3.2.4 Time Estimation Unit (TEU)

The TEU works based on two concepts: estimation and comparison. In the query broadcasting phase, the ST is attached to the query packet. We assume our network is synchronized. Each node that receives the query packet will estimate TTR from itself to the station based on the current time (CT) of receiving the query packet and the attached ST time:

$$TTR = CT - ST. \tag{1}$$

The TEU saves the TTR into the Neighbor Table. After the query broadcasting phase, each node can estimate how much time it takes to reach to the station from itself. In the response phase, each data sender node first computes the remaining time (RT) to reach the station.

$$RT = Deadline - (CT - ST)\,. \tag{2}$$

Next, the TEU compares the RT with its TTR, with the condition value of TTR>RT will send an alarm to DPSU. After receiving the alarm, the DPSU will change the condition from normal to critical mode.

3.2.5 Zone Estimation Unit (ZEU)

The ZEU is responsible for estimating the query zone. There are four different states for estimating the zone, based on API modes:

- *State 1: the ZEU and the SL mode*,
- *State 2: the ZEU and the SR mode*,
- *State 3: the ZEU and the NL mode*,
- *State 4: the ZEU and the NR mode*.

Following we will describe each state.
State 1: the ZEU and the SL Mode–The SL mode improves the efficiency of our query-based routing algorithm by restricting query flooding to a specified query zone. When the WSN starts its operation for querying a given node and getting information from it, the ZEU in the station S that will issue the queries will lack any zonal information. Therefore, the query mode used by station S at the beginning of the operations will typically be NL, which means that the entire region is assumed to be the query zone. Once the ZEU starts collecting information, the subsequent queries issued by station S can be made using the SL modes, thus exploiting the advantages of zonal broadcasting. The SL mode has two terms, expected zone and query zone, which we describe in the following paragraphs.

Expected zone–Consider a node S that needs to find a route to node D. Assume that node S knows that node D was at location L at time t_0, and that the current time is t_1. Then, the expected zone of node D, from the viewpoint of node S at time t_1, is the region that node S expects to contain node D at time t_1. Node S can determine the expected zone based on the knowledge that node D was at location L at time t_0 [14]. For instance, if node S knows that node D travels with average speed v or $Velocity$, then S may assume that the expected zone is the circular region of radius v(t_1 - t_0), centered at location L.

In general, the radius is computed based on following equation:

$$F = Velocity \times (t_1 - t_0) + epsilon. \tag{3}$$

In the equation, $Velocity$ is the average speed. t_1 is the current time and t_0 is the time of the previous location of node D. The constant $epsilon$ is used to keep radius nonzero in an immobility status.

If node S does not know a previous location of node D, then node S cannot reasonably determine the expected zone - in this case, the entire region that may potentially be occupied by the ad hoc network is assumed to be the expected zone [14].

Query zones-After estimating the expected zone, node S defines a query zone for the route query. All zonal broadcasting algorithms are essentially identical to flooding, with the modification that a node that is not in the request or query zone does not forward a route request to its neighbors. We describe the previous methods of computing the query zone and then introduce our proposed methods.

Previous query zones- Again, consider node S that needs to determine a route to node D. In the LAR1 algorithm, Ko et al. [14] proposed two methods of computing query (request) zones. They proposed a query zone, shown in Fig.3(a), that includes the expected zone. This is not an adequate query zone. All the paths from S to D may be located outside the query zone. Also, this type of zone does not include all the one-hop neighbors of station S and cannot support acceptable energy balancing in the station S area.

Ko et al. also proposed a query zone that is rectangular in shape (Fig.3(b)). Assume that node S knows the average speed V at which D can move, and that node S knows that node D was at location (Xd, Yd) at time t_0. Assume that at time t_1, node S initiates a new route discovery for destination D. Utilizing this knowledge, node S defines the expected zone at time t_1 to be the circle of radius F = v(t_1 - t_0) centered at location (Xd, Yd). The query zone is the rectangle whose corners are T_1, T_2, T_3 and T_4. When a node receives a query, the node discards it if the node is not within the rectangle specified by the four corners included in the route query. For instance, when node j receives the query originally sent from the station S and forwarded by node k, it will process the packet but it will not forward it, since j is not within the query zone delimited by the four corners. Instead, nodes i and k will process and forward the query, since they are inside the zone determined by the ZEU.

This rectangular zone has the problem as the previous zone: it does not include all the one-hop neighbors of node S and, therefore, energy management and balancing is not possible in the station domain. In a previous study [1], we presented a query zone for balancing energy in the station domain, shown in Fig.3(c). Unlike the method proposed by Ko et al., our proposed method considered all the station neighbors in the zone and can balance energy in the station domain very well.

Our proposed query zones- all the previous methods have one problem in common: zone size. The first zone, pictured in Fig.3(a), is very small and cannot cover enough nodes for effective energy balancing, especially around the station. The other method, shown in Fig.3(b), often covers a vast range of the network as a zone, and the nodes located at the corners of the zone (near points T_1 and T_2) will be useless. Another visible weakness of Fig.3(b) is all neighbors of the station are not included in the zone and therefore managing energy around station can be so difficult. Although the third zone computing method, Fig.3(c), considers all neighbors of the station in its zone but still its computed zones are often very big and consume more energy. In fact, using these nodes, that are located in the corners of zone, lead to long paths with long delay.

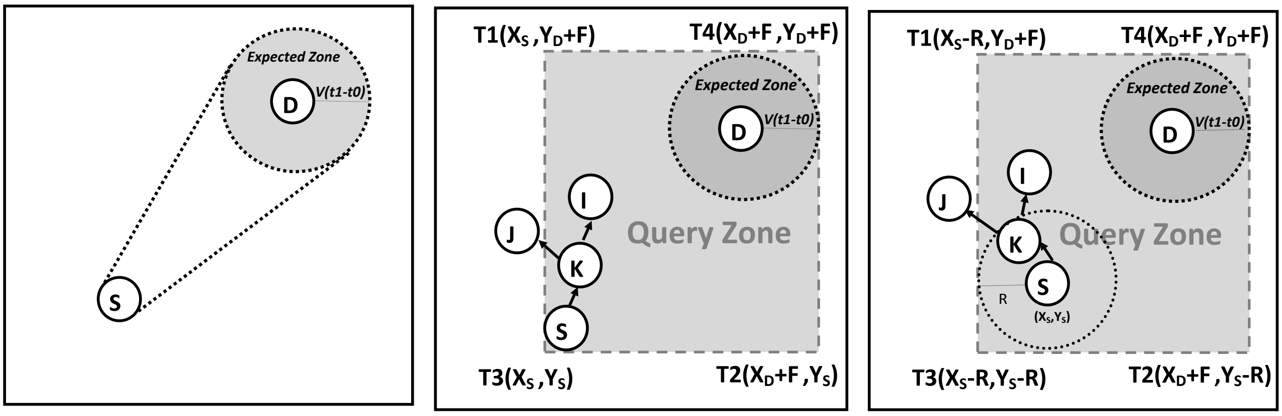
We propose a new query zone with an optimum size. This size optimization can reduce broadcasting query packet transmissions and energy consumption. We also introduce a very simple and efficient method for computing this optimum-size query zone. As Fig.4 shows, we can divide the zone into three parts: part 1, 2 and 3.

- *Part.1* includes all one-hop neighbors of the station S that are located inside its radio range. Therefore, technically each node that receives a query packet directly from the station considered itself inside the zone.
- *Part.2* can be considered as a rectangular shape. Its length is equal to distance between our source and destination. For computing its width, first we compute a Threshold. Width of the rectangular shape is considered two times longer than the Threshold. For getting the Threshold, first we compare radio range of the station (radios of part.1) and mobility range of destination (radios of part.3) and after that select the longest as our Threshold. Therefore the Threshold is whether radios of part.1 or part.3. A line that connects source and destination is passing from center of the rectangular shape. This line technically considered as a part.2 zone backbone and all intermediate nodes computes their distance from this backbone. If their distance from the backbone be less than the Threshold they are inside zone.
- *Part.3* of zone can be considered as a circular shape. Part.3 covers all possible locations that destination D can be there, we described it before in the Expected Zone and equation (3). Technically each query receiver node computes its distance from destination D (center of Part.3) and compare it with F in equation(3). If its distance be less than F it will be inside the zone.

Algorithm.1 shows details of our algorithm for computation of the proposed zone.

State 2: the ZEU and the SR mode–The ZEU acts almost the same way with the SR and SL modes. Instead of the destination location used in the SL mode, the ZEU uses the center position and the radius of the monitored region in the SR mode.

State 3: the ZEU and the NL mode–If the station node does not know the previous location of a destination node,



(a) (b) (c)

Fig. 3 Different previous zone schemas.

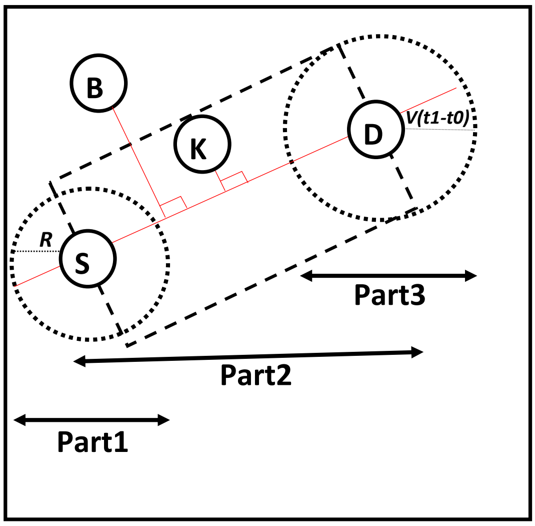


Fig. 4 Proposed query zone

then the station cannot reasonably determine the expected zone. In this case, the entire region that may potentially be occupied by the network is assumed to be the Query zone.

We note that this state occurs only once for each destination node, and that the station will find the position of each node after one query broadcast in NL mode. When the destination node receives the query packet, it includes its current location and current time in the data packet.

When the station receives this data packet, it records the location of the destination node. The station can use this information to determine the query zone for a future query.

State 4: the ZEU and the NR mode–When the station node wants to monitor the network domain to determine if there is an event or not, the entire region that may potentially be occupied by the network is assumed to be the query zone.

3.2.6 Data Path Selector Unit (DPSU)

The constellation of modules is mainly designed to assist the DPSU. The DPSU is the core routing module with the responsibility for choosing the next-hop during the data packet forwarding process. The DPSU can work in one of its two possible transmission modes: Normal and Critical. When the TCU warns the DPSU about shortage of time for delivery current packet, the DPSU will enter its critical mode and select the shortest (hop count) path to reach the station. The TEU is designed to assist the DPSU to select the appropriate mode every time.

If the TCU does not announce any warning, the DPSU will operate in its normal mode. It looks at its Neighbor Table and finds the neighbor with the highest probability in the M1 field (called $ID^{(M1)}$) and the neighbor with highest membership degree in the M2 field (called $ID^{(M2)}$). The highest probability neighbor in the M1 field is a selected

Algorithm 1: The Zone Detector Algorithm

Inputs : $\{S(X_S, Y_S), D(X_D, Y_D), I(X_i, Y_i), R, F\}$
Output : detecting a node is inside or outside the zone
Definition.1: S is our source or station
Definition.2: D is our destination
Definition.3: I is an intermediate node which receive the query
Definition.4: R is radio range of node S
Definition.5: F is radius of expected zone for destination: $F = V(t1 - t0)$
Definition.6: If (F>R) then Threshold= F else Threshold=R;
Definition.7: d is distance between intermediate node I and line passing from S and D points:
$d = \frac{|(X_D - X_S)*(Y_S - Y_i) - (X_S - X_i)*(Y_D - Y_S)|}{[(X_D - X_S)^2 + (Y_D - X_S)^2]^{\frac{1}{2}}}$.

foreach *zone detection request* **do**
  if *I am one-hop neighbor of S* **then**
    I am in Part.1 of the zone;
  else if $((X_D > X_i) and (X_i > X_S) and (d <= Threshold))$ **then**
    I am in Part.2 of the zone;
  else if $((X_D < X_i) and (X_i < X_S) and (d <= Threshold))$ **then**
    I am in Part.2 of the zone;
  else if *(distance between D and I is shorter than F)* **then**
    I am in Part.3 of the zone;
  else
    I am not in the zone;

Algorithm 2: The DPSU Algorithm

Input : $\{ID^{(M1)}, \mathcal{E}_{ID}^{(M1)}, H_{ID}^{(M1)}\}$
Input : $\{ID^{(M2)}, \mathcal{E}_{ID}^{(M2)}, H_{ID}^{(M2)}\}$
Input : $\{TEUalarm\}$
Output: next-hop node

foreach *packet to be forwarded* **do**
  if *Received alarm from TEU* **then**
    Send the packet to nearest neighbor to the station;
  // If no alarm;
  else if $(ID^{(M1)} == ID^{(M2)})$ **then**
    send the packet to the selected neighbor;
  // If IDs do not match then run tie-breaking rules;
  else if $(\mathcal{E}_{ID}^{(M1)} > \mathcal{E}_{ID}^{(M2)})$ && $(H_{ID}^{(M1)} < H_{ID}^{(M2)})$ **then**
    choose $ID^{(M1)}$ as the next-hop;
  else if $(\mathcal{E}_{ID}^{(M1)} < \mathcal{E}_{ID}^{(M2)})$ && $(H_{ID}^{(M1)} > H_{ID}^{(M2)})$ **then**
    choose $ID^{(M2)}$ as the next-hop;
  else choose the one with the highest energy;

neighbor when using the learning automata technique (the M1:LA module) and the highest membership degree in the M2 field is a selected neighbor by means of the fuzzy set technique (the M2:FS module).

The Decision Maker (DM) will then select the next hop. Note that if the selections made by the M1:LA and M2:FS modules match, then the node selected is chosen as the next-hop. Otherwise, the DM runs a basic sequence of tie-breaking rules until the next-hop is selected.

The processing of the DPSU module is summarized in Algorithm 2. In this algorithm $\mathcal{E}_{ID}^{(M1)}$ and $H_{ID}^{(M1)}$ are the energy level and hop count, respectively, of selected neighbor $ID^{(M1)}$ by means of learning automata and $\mathcal{E}_{ID}^{(M2)}$ and $H_{ID}^{(M2)}$ are the energy level and hop count, respectively, of selected neighbor $ID^{(M1)}$ by utilizing the fuzzy set technique.

3.2.7 Membership Computer Unit (MCU)

The theory of fuzzy sets was introduced by L. Zadeh in 1965 [24]. Since the pioneering work of Zadeh, there has been a great effort to obtain fuzzy analogues of classical theories. Fuzzy set theory is a powerful tool for modeling uncertainty and for processing vague or subjective information in mathematical models. Their main directions of development have been quite diverse and it has been applied to a great variety of real problems. The notion central to fuzzy systems is that truth values (in fuzzy logic) or membership values (in fuzzy sets) are indicated by a value on the range [0, 1], with 0 and 1 representing absolute Falseness and absolute Truth, respectively.

The RER algorithm considers a fuzzy set; A. Fuzzy set A includes all possible candidates or neighbors. The set also has a membership function. The membership function maps each value (neighbor) to a membership value on the range [0, 1].

Membership function computation–The membership function consists of three factors, $K1$, $K2$ and $K3$, on a range of [0,1]. A fairly efficient way to compute the membership degree of neighbors can be achieved by multiplying these factors together. All three factors of each neighbor will thus be multiplied together to get neighbor's membership degree. Assume there are n neighbors. Computing of the factors for the membership function of the i_{th} neighbor is described below in more detail:

$$\begin{cases} K_1 = 1 - \left(\dfrac{Hop_i}{MaxHop}\right), \\ K_2 = \left(\dfrac{Energy_i}{MaxEnergy}\right), \\ K_3 = 1 - \left(\dfrac{Distance_i}{MaxDistance}\right). \end{cases} \tag{4}$$

The membership degree of the i_{th} neighbor can then be computed based on the following function and inserted into the M_2 field of the i_{th} neighbor:

$$M_2 = MembershipFunction = K_1 \times K_2 \times K_3. \quad (5)$$

3.2.8 Probability Computation Unit (PCU)

As we mentioned earlier, when a node (i.e., node i) receives a query packet from a neighbor for the first time (i.e., from neighbor K), this produces a new entry in its Neighbor Table. The Neighbor Table is composed of fields, and each part of the data has to be stored in its related field (described in Section 3.2.3).

The PCU can then compute the probability of neighbor K from the information contained in the Neighbor Table received from neighbor K. The probability Pk(t) associated with neighbor K is computed according to the equation (6).

$$Pk(t) = \frac{1}{3}\left(\frac{\mathcal{E}_k(t)}{\sum_{m=1}^{N_i}\mathcal{E}_m(t)} + \frac{\frac{1}{D_k(t)}}{\sum_{m=1}^{N_i}\frac{1}{D_m(t)}} + \frac{\frac{1}{H_k(t)}}{\sum_{m=1}^{N_i}\frac{1}{H_m(t)}}\right)$$
$$k \le N_i. \quad (6)$$

As stated above, the probability Pk(t) is computed using the PCU, where $\mathcal{E}_m(t)$ is the energy level advertised by neighbor m, N_i is the size of node i's Neighbor Table (including now node k), $D_m(t)$ is the distance advertised by neighbor m to the station S, computed based on equation (7) where (x1,y1) and (x2,y2) are the positions of the station and the current neighbor already saved in Neighbor Table. The sums in the denominators represent the terms to normalize the probabilities and to make $\sum_{k=1}^{N_i} P_k(t) = 1$.

$$D = \left((Y2 - Y1)^2 + (X2 - X1)^2\right)^{\frac{1}{2}}. \quad (7)$$

The rationale of using equation (6) is that it produces a good balance between energy and distance, though at the cost of the potential re-computation of the probabilities immediately after each query packet is received, since the sum of the probabilities for all neighbors must be equal to one.

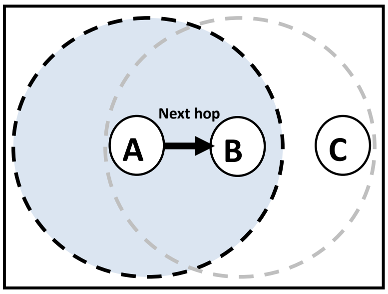
3.2.9 Error Detector Unit (EDU)

As its name indicates, the EDU is designed to detect errors. Most routing protocols use an Acknowledge packet to find if the next hop has received the packet or not. The sender node sends the packet to its next hop and the receiver node sends back an Acknowledge packet. If the sender does not receive the Acknowledge packet from the receiver, it determines that the link is broken.

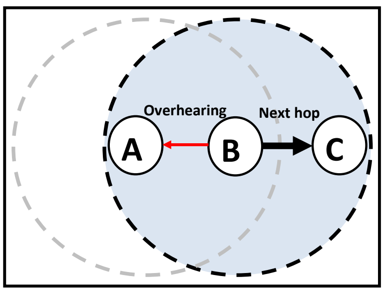
RER does not use an Acknowledge packet. Instead, it verifies links by use of an overhearing technique. For example, in Fig.5, node A sends a data packet to B. When B sends the data packet to the next hop, i.e., node C, node A receives the data packet again via overhearing. If node A does not receive the data packet again after a certain time, it considers the link with B to be broken. In this case, it selects another node to send the data. The RER does not need to use an Acknowledge packet, thereby saving more energy than traditional protocols.

3.2.10 Probability Update Unit (PUU)

The basics of the mechanism are illustrated in Fig.5, and it works as follows: The M1:LA module in node A offers the neighbor with the highest probability, from the M1 field of Neighbor Table, as its offered next hop (neighbor B in this case), and then it waits for final decision by the DM module of the DPSU. If the DM selects the same node (node B in this case) as a next hop, the DPSU informs the M1:LA module (learning automata) whose offered neighbor was selected as a next hop.



(a) Phase (1)



(b) Phase (2)

Fig. 5 Update probability and error detection scheme.

Thus, in fact, the PUU will be enabled if the learning automata (the M1:LA module) and the DM of DPSU select the same neighbor as a the next hop. When node B receives the data packet, its NUU updates the piggybacked energy level of node A in its Neighbor Table and all the other neighbors of A overhear the data packet and perform the same updates as B, although they discard the packets immediately after processing them. The routing process continues now with node B selecting node C as its next hop. When B sends the data packet to C, node A is the one that overhears the packet sent by B; its NUU thereby updates the energy level of the latter and then its PUU will update probability of node B.

The PUU functions based on piggybacking and overhearing techniques; it can compute and mutually update the probabilities in the Neighbor Tables according to the energy levels, hop count and distances obtained from the neighbors.

In the example, if the metrics received from node B are acceptable, then node B is rewarded by the learning automaton in A, and the probability associated to B is increased in node A's Neighbor Table. Otherwise, B is penalized and its probability is decreased.

In our model, we considered four behavioral cases for rewarding or penalizing a neighbor B.

In the first case, the energy-distance-hop relationship is below the average, and thus the learning automata in A will penalize node B with a factor β.
where $<\mathcal{E}_A(t)>= \sum_{m=1}^{N_i} \mathcal{E}_m(t)/N_i$ represents the average energy of the neighbors of node A, and $\mathcal{E}_B(t)$ stands for the energy level obtained from B. Likewise, $<D_A(t)>$ represents the average distance of the neighbors of A to the station S, while $D_B(t)$ represents the distance to S reported by node B. $<H_A(t)>$ represents the average hop counts of the neighbors of A to the station S, while $H_B(t)$ represents the hop count to S reported by node B. In the second case, we consider a lower penalization. The selected penalization is $\beta/2$. In the third case, node A will reward node B with $\alpha/2$. We consider that the best case occurs in the fourth case.

$$\begin{cases} Case1: \frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} + \frac{<D_A(t)>}{D_B(t)} + \frac{<H_A(t)>}{H_B(t)} < 3, \\ Case2: \frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} + \frac{<D_A(t)>}{D_B(t)} + \frac{<H_A(t)>}{H_B(t)} = 3, \\ Case3: 3 < \frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} + \frac{<D_A(t)>}{D_B(t)} + \frac{<H_A(t)>}{H_B(t)} \leq 3.5, \\ Case4: 3.5 < \frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} + \frac{<D_A(t)>}{D_B(t)} + \frac{<H_A(t)>}{H_B(t)}. \end{cases} \tag{8}$$

Reward computation — The reward parameter α is used during the update mechanism in order to grant more priority to the nodes giving them more possibilities to forward the response packets to the station. The value of α is computed using:

$$\alpha = \lambda_\alpha + \delta_\alpha \left(\frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} \times \frac{<D_A(t)>}{D_B(t)} \times \frac{<H_A(t)>}{H_B(t)} \right), \tag{9}$$

where λ_α is the minimum reward granted to a well-positioned node, and δ_α is the limiting factor for the reward.

Penalty computation — Similarly, we use:

$$\beta = \lambda_\beta + \delta_\beta \left(\frac{\mathcal{E}_B(t)}{<\mathcal{E}_A(t)>} \times \frac{<D_A(t)>}{D_B(t)} \times \frac{<H_A(t)>}{H_B(t)} \right)^{-1}, \tag{10}$$

where analogously to the reward mechanism, λ_β is the minimum penalty, and δ_β is the limiting factor. Note that in equation (9) and (10), the better (or worse) the energy–distance relationship the greater the reward (or penalization) assigned for node B.

Upon obtaining the energy and distance metrics from node B, the learning automata in node A will update the probabilities of its N_A neighbors based on equations (11) and (12).

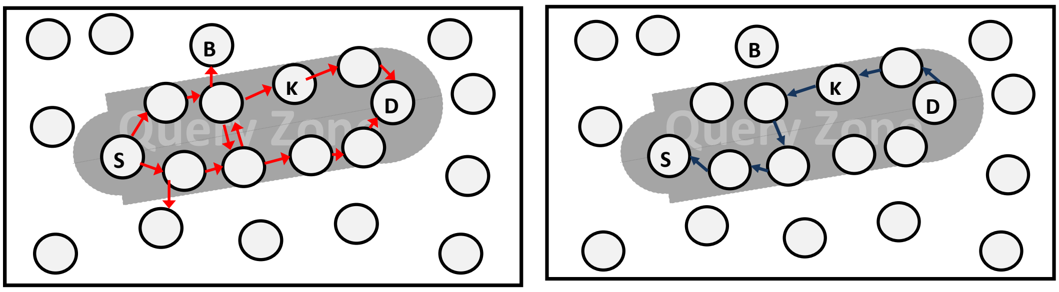
The former applies for the rewarding cases, i.e., the third and fourth cases described above, with $x_\alpha = \alpha/2$ and $x_\alpha = \alpha$, respectively. The latter corresponds to the penalization cases, that is, the first and second cases, with $x_\beta = \beta$ and $x_\beta = \beta/2$, respectively.

$$\begin{cases} P_B(t_{n+1}) = P_B(t_n) + x_\alpha[1 - P_B(t_n)] \\ P_k(t_{n+1}) = (1 - x_\alpha)P_k(t_n) \quad \forall k \mid k \neq B \wedge k \leq N_A, \end{cases} \tag{11}$$

$$\begin{cases} P_B(t_{n+1}) = (1 - x_\beta)P_B(t_n) \\ P_k(t_{n+1}) = \frac{x_\beta}{N_A - 1} + (1 - x_\beta)P_k(t_n) \\ \qquad \forall k \mid k \neq B \wedge k \leq N_A. \end{cases} \tag{12}$$

3.3 RER Mechanism

RER is an energy-aware routing protocol designed to consider packet delivery delay while routing packets across a network. RER balances the load among the different sensors with a twofold goal: preventing the sensors from running out of battery while keeping the routes to reach the destinations relatively short. It also offers a soft real time system. RER can be divided into two phases: query broadcasting and data forwarding.



(a) Query broadcasting phase. (b) Data forwarding phase.

Fig. 6 RER phases.

- *Query broadcasting phase* —When the WSN starts its operation, a ZEU in the station S that will issue the queries will have no zonal information. Therefore, the query modes used by station S at the beginning of the operations will typically be NL or NR, which means that the entire region is assumed to be the query zone.
  Once the ZEU starts collecting information, the subsequent queries issued by the station S can be made using the SR or the SL modes, thus exploiting the advantages of zonal broadcasting.
  In general terms, station S will gather zonal information in its ZEU, and whenever required it will generate a query packet in which it will broadcast some items such as its ID, the query mode (NR, NL, SR, or SL), its position, the zone information, and optionally, the destination ID. The nodes receiving the query packet can forward or discard it depending on their location.
  For instance, on the Fig. 6(a), when node B receives the query originally sent from station S, it will process the packet but it will not forward it, since B is not within the query zone. Instead, node K will process and forward the query given that it is inside the zone determined by the ZEU.
  In brief, the nodes within the query zone distribute the queries complementing the information originally sent by the station S with their own Id, their energy level, the procedure start time, their position, hop count, distance to the station, and a list of hops to prevent forwarding loops. This process is repeated until a destination is found.

- *Data forwarding phase* — When the destination or event witness node receives the query packet, it replies by sending a data packet. At this point, every node in the zone knows the energy levels of their neighbors and the distance and hop count from them to the station S.
  As shown in Fig.6(b), the response to the station could use a different path, since this will depend on the primary neighbor selected by the DPSU.

4 Performance Evaluation

In this section, we evaluate the RER's performance by comparing it to the following routing protocols: Rumor [6], as a basic query-based routing protocol, and EQR [1], as a new query-based routing protocol. To this end, we used the GloMoSim simulator developed by UCLA [25]. The simulation model used and the results we obtained with it are described below.

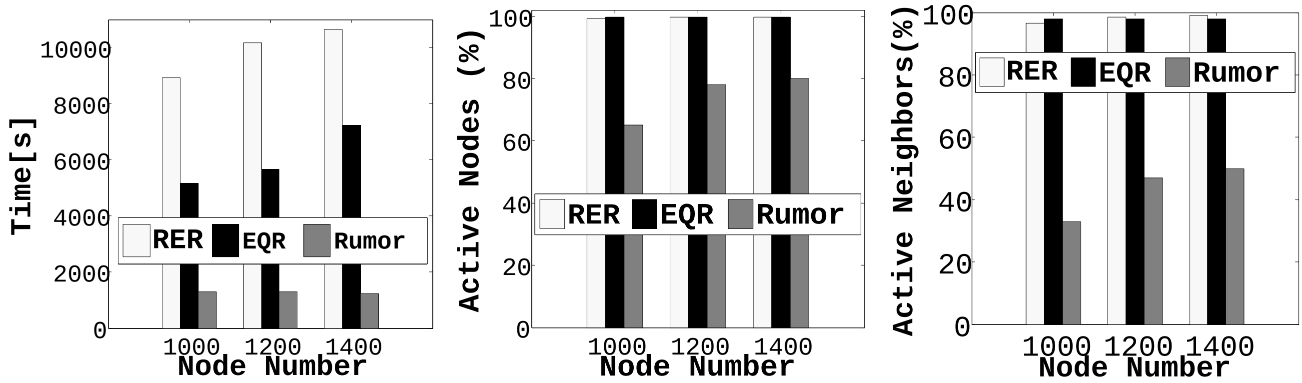
4.1 Simulation Model

We used a surface that was 1000 m $\times$ 1000 m. The radio range was set to 177 m, with an available bandwidth of 2 Mbps and a radio transmission(TX) power of 4 dBm. Each simulation had a 4-hour duration, and the tests were run under various conditions, such as with different amount of sensors, namely, 1000, 1200, and 1400 nodes, and also with 10 different amounts of seeds. Moreover, the placement of the sensors in the terrain and their initial energy levels were selected randomly. It is worth highlighting that, even though the placement and initial energy of the nodes were set randomly, once set those factors remained fixed for rest of the trials to obtain comparable results across experiments.

In the simulations presented here, the traffic in the network is always initiated by a source station S, which periodically acquires information from a particular sensor d. The sensor d moves at a speed of 40 Metre/Hour. Once the query is received at d, the sensor will immediately send back the response to S with the requested information.

Scenario I—In this scenario, we assume a critical situation, where the energy levels for transmission mode are very low. Under these conditions, we evaluate the different routing schemes considering three different tests:

- *Test 1: Time until the first node runs out of battery power—* This test is one of the indicators of the effectiveness of the routing schemes in terms of energy management. In general, those with the capacity to balance the energy consumed should last longer without node failure.

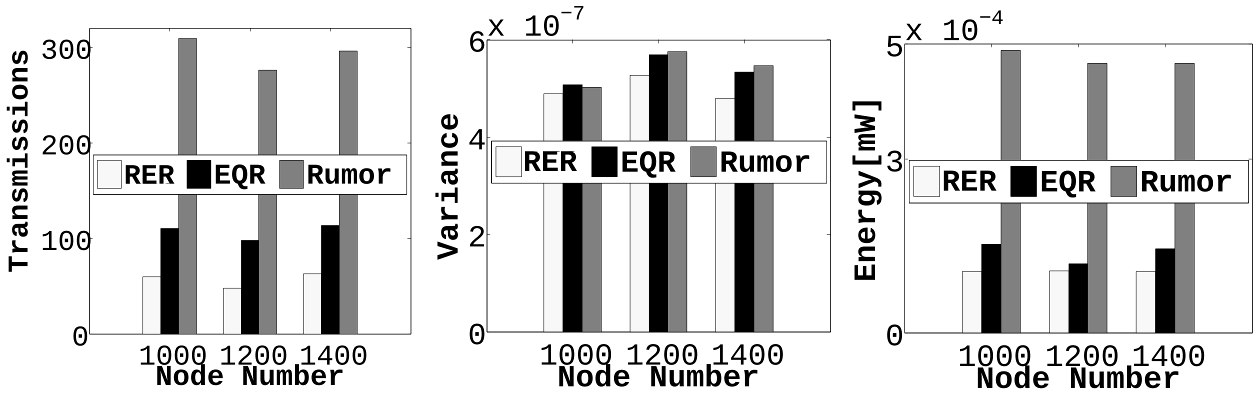


(a) *Test1:* Time until the first node runs out of battery.

(b) *Test2:* Fraction of active nodes.

(c) *Test3:* Fraction of active neighbors of S.

Fig. 7 Tests results for Scenario I.



(a) *Test4:* Average data packet transmission.

(b) *Test5:* Variance.

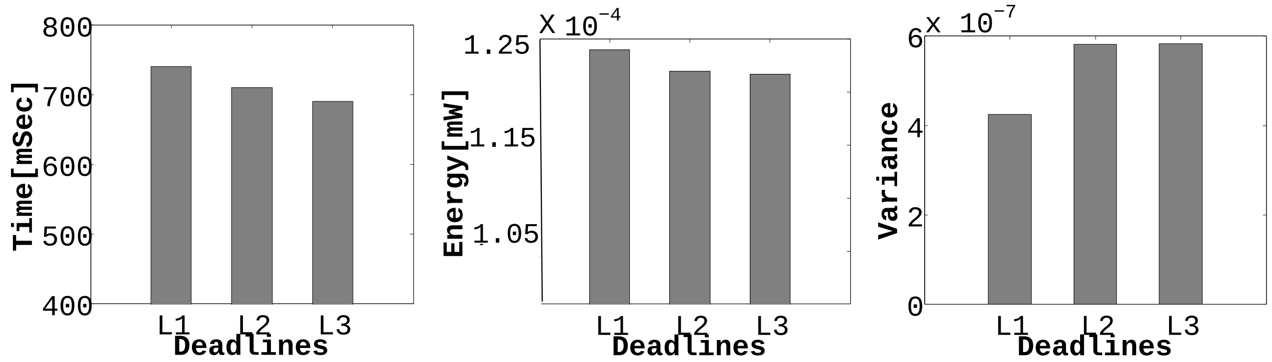
(c) *Test6:* Average energy consumption.

Fig. 8 Tests results for Scenario II.

– *Test 2: Fraction of active nodes at the end of the simulation*—This test gets the total number of sensors that are active (alive) for each routing scheme during a simulation period of 2 hours, providing an indicator of the capacity of the routing schemes for saving energy. Those protocols with ability of balancing the energy consumed should have lower number of node failure than the others.
– *Test 3: Fraction of active neighbors of the station S at the end of the simulation*—Traffic load around station is very heavy because a station is source of the query packets and destination of the data packets. Therefore, managing energy of the station neighbors and keeping the station connected to network is very important. This test shows the ability of the different routing schemes to keep the station S connected. As in the case of *Test 2*, the simulation period for this test is 2 hours.

Scenario II—In this scenario, the energy levels of the sensors are set sufficiently high so as to avoid experiencing node failures during the simulation runtime. Our goal in this case is to compare the fairness in terms of energy consumption. In order to avoid bias in the comparison, we ensure that all the routing schemes transmit the same amount of data, and that this occurs without node failures. We carry out three tests to examine how the routing schemes save and manage energy in regular operation mode.

– *Test 4: Average data packet transmission*—This test computes average number of hops that a data packet should travel to reach to the station for each protocol. It provides another indicator of which routing scheme is more efficient in saving energy.
– *Test 5: Variance in the remaining energy levels for the neighbors of station S*—This test considers one-hop neighbors of the station and computes a variance in energy level for them. It allows us to examine which routing scheme is the best at performing energy balancing among the nodes close to the station.
– *Test 6: Average energy consumption*—This test computes average energy consumption of a node for each protocol.



(a) *Test7:* Ene-to-end delay. (b) *Test8:* Average energy consumption. (c) *Test9:* Variance.

Fig. 9 Tests results for Scenario III.

It provides another indicator of which routing scheme is more efficient in managing energy.

Scenario III—In this scenario, we consider three different levels of deadline: L1(long), L2(medium), L3(short).

We also carry out three tests to examine how the RER protocol can react to these different types of time constraints.

– *Test 7: Average end-to-end delay*—This test shows how RER can adapt itself to different deadlines.
– *Test 8: Average energy consumption*—This test shows how energy consumption is changed based on different deadlines.
– *Test 9: Variance in the remaining energy levels for the neighbors of station S*—This test identifies which deadline level produces better energy balancing among the nodes close to the station.

4.2 Simulation Results

Scenario I—The most commonly used measure of network lifetime is the time until the first node runs out of battery energy. In RER the first sensor fails after $\sim$ 8000 to $\sim$ 11000 seconds depending on the number of nodes present in the network(see Fig. 7(a)). The time in which the first node runs out of battery is relatively shorter for EQR (fails after $\sim$ 5000 to $\sim$ 7000 seconds) and significantly shorter for Rumor that fails around 1000 seconds. Fig.7(b) is a good indicator for evaluating energy management of protocols. While Fig.7(b) shows ability of energy management in the network Fig.7(c) specialized to show energy management of protocols only around the station node. Fig.7(b) and Fig.7(c) show that the RER is much better than the more traditional Rumor and that it is relatively similar to the new EQR protocol. In brief, considering the three parts of Fig.7, even though in low battery situations there is no big difference between EQR and RER in terms of the number of node failures, it is clear RER can keep a network alive longer than EQR.

Scenario II— We evaluate these protocols in normal energy situations.

Fig.8(a) shows average number of hops that a data packet should travel to reach to the station for each protocol. The Rumor is the worst routing protocol, mostly because Rumor selects its next hops randomly. EQR selects next hops based on learning automata and RER selects them based on both fuzzy set and learning automata. It is clear that selections based on chance (Rumor) leads to a higher number of transmissions than a systematic selection process (EQR and RER). A higher number of transmissions also should consume more energy (see Fig.8(c)). One more important point that we can extract from Fig.8(b) and Fig.8(c) together is the RER not only is an energy saver protocol but also it is an energy balancer routing protocol.

Actually, beyond merely comparing the particular values obtained in each figure, the most important conclusions that can be extracted from Fig.8(a), Fig.8(b) and Fig.8(c) as a whole are basically the following. The results show that the combination of a fuzzy set technique and learning automata can improve energy balancing, and more importantly, that the combined operation (RER's use of fuzzy set plus learning) can work better than only one technique(EQR). Our new proposed zone could also reduce the number of packet transmission and save more energy than previous versions.

Scenario III—As mentioned above, RER also acts as a delay-aware routing protocol. Fig.9 (a) shows how RER sets its end-to-end delay based on different deadlines. L1 is a long period deadline and so RER does not receive any alarm from its TEU. Therefore, the DPSU acts in its normal mode and selects its next hops based on energy and distance factors. Therefore, as Fig.9 (c) shows we have the best energy balancing by using L1. However, with the L3 deadline, there is no time to deliver data packet to the station and so that TEU sends an alarm to the DPSU to select the closest neighbor to the station. In L3 the most important factor is time and therefore a shortest path is selected. By selecting the shortest possible path and reducing number of hops in L3, we expect and also Fig.9(b) shows that energy consumption is reduced in comparison with L1. Selecting the shortest path to reduce end-to-end delay causes increasing variance of L3 in comparison with L1 (Fig.9(c)).

Generally, results of the Scenario.III showed that the RER is a flexible protocol and can adapt itself with different deadlines and time constraints.

5 Conclusion

In this paper we studied energy-aware query-based routing protocols. From the routing perspective, we have observed that the current destination-initiated query-based routing protocols can be considerably improved, especially, if we aim for a better balance between the energy savings and energy balancing objectives. We have proposed a new real-time energy saver/balancer routing protocol. We simulated and compared our routing protocol with traditional Rumor and newer EQR protocols. Indeed, nine different types of tests were carried out and described, and in most of these tests indicated that the RER obtained significantly better results.

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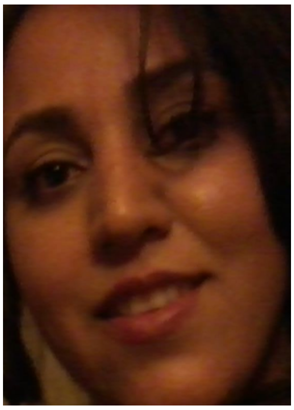

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